

# Formation of the Small Magellanic Cloud: ancient major merger as a solution to the kinematical differences between old stars and HI gas

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## ABSTRACT

Recent observations of the Small Magellanic Cloud (SMC) have revealed that the HI gas shows a significant amount of rotation ( $V_c \sim 60 \text{ km s}^{-1}$ ), while no or little rotation is evident for the old stellar populations. We suggest that this unique kinematical difference between these components in the SMC can be caused by a major merger event which occurred in the early stage of the SMC formation. Our simulations show that dissipative dwarf-dwarf merging can transform two gas-rich dwarf irregulars into a new dwarf, which consists of a spheroidal stellar component and a rotating extended HI disk. The remnant of this dwarf-dwarf merging shows significantly different kinematics between stars and gas, in the sense that a gas disk rotates rapidly while a stellar component shows little rotation. We thus suggest that the simulated dwarf having a dynamically hot spheroid and an extended gas disk finally evolves into the present SMC after efficient stripping of the outer gas via tidal fields of the Galaxy and the Large Magellanic Cloud. We also suggest that spatial distributions and kinematics of RGB and AGB stars with different ages in the possible spheroidal component of the SMC can provide valuable information on whether and when a past major merger event really occurred in the SMC.

*Subject headings:* Galaxy: halo – galaxies:evolution – galaxies:stellar content

## 1. Introduction

Recent high-resolution HI observations have revealed that the SMC has a significant amount of rotation with a circular velocity ( $V_c$ ) of  $\sim 60 \text{ km s}^{-1}$  (Stanimirović et al. 2004,

S04). The observed  $V_c$  implies that the SMC has a total mass of  $\sim 2.4 \times 10^9 M_\odot$  within the central 3 kpc and thus appears to have no dark matter (S04). The apparent lack of dark matter halo in the SMC has been suggested to result either from some observational uncertainties in estimating the total mass or from very low density of the dark matter halo (Bekki & Stanimirović 2008).

The latest survey of 2046 red giant stars has suggested that the older stellar components of the SMC have a velocity dispersion ( $\sigma$ ) of  $\sim 27.5 \text{ km s}^{-1}$  and a maximum possible rotation of  $\sim 17 \text{ km s}^{-1}$  (Harris & Zaritsky 2006). This result is consistent with other kinematical studies based on radial velocities of other old and intermediate-age stellar populations such as PNe and carbon stars (e.g., Dopita et al. 1985; Suntzeff et al. 1986; Hatzidimitriou et al. 1997), which implies that the older stellar component is a spheroid that is primarily supported by its velocity dispersion. These observations and HI ones (e.g., S04) thus suggest that there is a remarkable difference in kinematics between older stellar populations and HI gas in the SMC.

Bekki & Chiba (2008) pointed out that the rotating gas disk of the SMC can be gradually formed via gas accretion *after the formation of the older spheroidal component*. They also pointed out that directions of intrinsic spin axes of older stars and gas in the SMC could be significantly different to each other, like polar-ring galaxies. They did not however discuss how the dynamically hot stellar spheroid composed of older stars in the SMC can be formed. If the SMC really has a dynamically hot spheroid composed mostly of older stellar populations, a key question is why the SMC has *both* a dynamically hot stellar spheroid and a rotating gas disk.

The purpose of this *Letter* is to suggest a new possible scenario that the SMC could have experienced a major merger event long time ago in which both the older stellar spheroid and the rotating gas disk were created. Based on numerical simulations, we show that ancient dwarf-dwarf merging can transform two gas-rich dwarf disks into one gas-rich spheroid with an extended gas disk with rotation. We explain why the SMC *as a (dwarf) spheroidal galaxy* could have a larger amount of HI gas ( $> 10^9 M_\odot$ ) in the context of the ancient major merger event. We also discuss advantages and disadvantages of this scenario in explaining the observed structural and kinematical properties of stars with different ages in the present SMC.

Although recent extensive and systematic numerical simulations have investigated physical properties of remnants of mergers between luminous disk galaxies (e.g., Naab et al. 2006; Di Matteo et al. 2007), they did not investigate models in which *merger progenitors are low-mass dwarfs and have very extended HI disks*. The extended HI disks are one of the characteristics of gas-rich dwarfs (e.g., Hunter 1997; Warren et al 2004) and modeled prop-

erly by the present study for the first time. The extended HI disks of merger progenitors can play a key role in forming extended gas disks surrounding old spheroids in merger remnants, as shown later in this paper.

## 2. The model for the merger scenario

We investigate chemodynamical evolution of gas-rich mergers between dIs with stellar and gaseous disks embedded in massive dark matter halos by using our original chemodynamical codes (Bekki & Chiba 2005, BC05) that can be run on GRAPE systems (Sugimoto et al. 1990). Since the details of numerical techniques and methods (e.g., ways to model chemical enrichment processes) are already given in the above papers, we briefly describe them in the present paper. We adopt the Burkert profile (Burkert 1995) for the radial density profile of the dark matter halo of a dI, because it can be consistent with rotation curve profiles of dIs (Burkert 1995). The total masses of the dark matter ( $M_{\text{dm}}$ ) and the baryonic component ( $M_{\text{b}}$ ) for the dI are set to be  $8.0 \times 10^9 M_{\odot}$  and  $2.0 \times 10^9 M_{\odot}$ , respectively. The dark matter halo has a large core radius ( $r_c$ ) of 3.5 kpc and the truncation radius of  $3.4r_c$  (Burkert 1995).

The dI is described as a pure disk (without a bulge) with the initial size of 5 kpc and the radial ( $R$ ) and vertical ( $Z$ ) density profiles starting from a thin disk are assumed to be proportional to  $\exp(-R/R_0)$  with scale length  $R_0 = 1$  kpc and to  $\text{sech}^2(Z/Z_0)$  with scale length  $Z_0 = 0.2R_0$ , respectively. The HI diameters of gas-rich galaxies are generally observed to be larger than their optical disks (Broeils & van Woerden 1994). A small fraction of low luminosity galaxies have HI gas envelopes extending out to 4–7 optical radii (e.g., Hunter 1997) with HI mass to light ratios up to  $\sim 20 M_{\odot} L_{\odot}^{-1}$  (Warren et al. 2004). Observational studies showed that there are threshold gas densities for galaxy-scale star formation in disk galaxies (Kennicutt 1998). Guided by these observations, we assume that the disk can contain only gas for  $R > R_{\text{th}}$ , where  $R_{\text{th}}$  is a parameter for the stellar disk size, owing to the lower gas density for  $R > R_{\text{th}}$ . The fraction of gas mass ( $M_{\text{g}}$ ) to the sum of stellar ( $M_{\text{s}}$ ) and gaseous ones is represented by  $f_{\text{g}}$  and assumed to be a free parameter. The size of gas disk ( $R_{\text{g}}$ ) is set to be four times larger than that of stellar one ( $R_{\text{s}}$ ) in the present study, which is consistent with those of some dIrr’s (e.g., Hunter 1997).

Star formation is modeled by converting the collisional gas particles into collisionless new stellar particles according to the algorithm of star formation described below. We adopt the Schmidt law (Schmidt 1959) with exponent  $\gamma = 1.5$  ( $1.0 < \gamma < 2.0$ , Kennicutt 1998) as the controlling parameter of the rate of star formation. The stars formed from gas are called “new stars” whereas stars initially within a disk are called “old stars” throughout this

paper. Chemical enrichment through star formation and supernova feedback are assumed to proceed both locally and instantaneously in the present study. The values of chemical yield and return parameter are 0.004 and 0.3, respectively, and the initial gaseous metallicity in the dI is  $[\text{Fe}/\text{H}] = -1.0$ . The total masses of old and new stars are referred to as  $M_{\text{os}}$  and  $M_{\text{ns}}$ , respectively.

The mass ratio of the two merging dIs ( $m_2$ ), the pericenter distance ( $r_p$ ), and the eccentricity ( $e_p$ ) are assumed to be free parameters. The orbit of the two dIs is set to be inclined by 45 degrees with respect to the  $xy$  plane and the distance between the center of mass of the two dIs is 20 kpc. The spin of each galaxy in a merger is specified by two angles  $\theta_i$  and  $\phi_i$ , where suffix  $i$  is used to identify each galaxy.  $\theta_i$  is the angle between the  $z$  axis and the vector of the angular momentum of a disk.  $\phi_i$  is the azimuthal angle measured from the  $x$  axis to the projection of the angular momentum vector of a disk onto the  $xy$  plane.

Although we run many models with different parameters, we show only one model with  $f_g = 0.7$ ,  $R_{\text{th}} = 1.25$  kpc (i.e.,  $R_g = 4R_s$ ),  $m_2 = 0.5$ ,  $r_p = 2$  kpc,  $e_p = 1.0$ ,  $\theta_1 = 30^\circ$ ,  $\theta_2 = 120^\circ$ ,  $\phi_1 = 90^\circ$ ,  $\phi_2 = 30^\circ$ . This is mainly because the merger remnant of the model shows more clearly both kinematical differences between gas and stars and extended gas disk with rotation. The simulations have mass and size resolutions of  $10^4 M_\odot$  and 90 pc, respectively, and both the GRAPE-SPH code (Bekki & Chiba 2006) and the one adopted in BC05 are used for each model. We show the results of the model based on the same code as BC05 and will give the results based on GRAPE-SPH codes in our forthcoming papers (Bekki & Chiba 2008) in order to describe in detail the dependences of the results on modeling of the interstellar medium.

One of the new ingredients in the present simulation is that the merger progenitor dIs have very extended gas disks that are consistent with observations (e.g., Hunter 1997; Warren et al. 2004). We confirm that the extended gas disks in merger progenitor dIs play a vital role in forming the extended gas disk surrounding old stars in the merger remnants irrespective of initial gas mass fractions. This importance of extended gas disks was not investigated in previous simulations (e.g., Naab et al. 2006). In the present study, we consider that the dI-dI merging leading to the formation of the SMC occurred long before the strong LMC-SMC interaction commenced about 3 – 4 Gyr ago (BC05): possibly this merger event might have occurred far away from the Galaxy in order to have the low relative velocity between two merging dIs. We consider that the low relative velocity would be possible, because the two dIs were either initially a pair or in a very small group (of galaxies) with a smaller circular velocity that merged the outer region of the Galaxy’s halo long time ago.

### 3. Results

Figure 1 describes how dwarf-dwarf merging can transform two dIs into a new dwarf with a central spheroid and an extended gas disk. Owing to strong violent relaxation in the central region of the merger, the inner stellar disks are completely destroyed and form a slightly flattened spheroidal component with a half-mass radius of 2.0 kpc. Although the gas disk of the larger dI can be temporarily disturbed strongly by the merging, it finally becomes a new extended gas disk after dissipative merging with that of the smaller dI. The star formation rate can reach the maximum value of  $2.4\text{M}_\odot \text{ yr}^{-1}$  at  $T = 0.6$  Gyr during the merging owing to efficient and rapid transfer of gas toward the central region of the merger. New stars formed during merging also show a significantly flattened spheroidal distribution with a half-mass radius of 1.3 kpc. The outer low-density part of the stellar spheroid composed of metal-poor stars ( $-0.9 < [\text{Fe}/\text{H}] < -1.0$ ) might well be identified as a stellar halo around the remnant.

Figure 2 shows that the final total mass of the remnant within the central 3 kpc at  $T = 1.7$  Gyr is about  $2.8 \times 10^9 \text{M}_\odot$ , which is consistent with the observation by S04. However, the total stellar mass (i.e.,  $M_s = M_{\text{os}} + M_{\text{ns}}$ ) within the central 3 kpc is  $0.4 \times 10^9 \text{M}_\odot$  and thus appears to be significantly smaller than the observed one ( $M_s = 1.8 \times 10^9 \text{M}_\odot$ ) of the present SMC with the assumed mass-to-light-ratio of  $\sim 1$  (S04). The total mass of the remaining gas is  $1.6 \times 10^9 \text{M}_\odot$  and most of the gas is located at  $R > 1$  kpc. The gas can be used for further star formation in the remnant so that the total stellar mass within the central 3kpc can dramatically increase within several Gyrs.

Figure 3 shows how radial profiles of line-of-sight velocities ( $V$ ) and velocity dispersions ( $\sigma$ ) are different between stellar and gaseous components. The gaseous component clearly shows a large amount of rotation with the maximum  $V$  of  $59 \text{ km s}^{-1}$  and a small central velocity dispersion of  $\sigma = 24 \text{ km s}^{-1}$  (i.e.,  $V/\sigma \sim 2.5$ ) if the remnant is seen almost from the edge-on. The stellar component, on the other hand, shows a smaller amount of rotation of  $V \sim 20 \text{ km s}^{-1}$  and a larger maximum velocity dispersion of  $\sigma \sim 48 \text{ km s}^{-1}$  (i.e.,  $V/\sigma \sim 0.4$ ). The simulated high and low  $V/\sigma$  in gas and stars, respectively, are consistent with the observations of the SMC (S04; Harris & Zaritsky 2006), which means that the model can reproduce well the present SMC with a possible spheroid with dynamically hot kinematics and an extended gas disk with rotation.

Figure 4 shows that there is a negative metallicity gradient within the central 2 kpc ( $\Delta[\text{Fe}/\text{H}]/\Delta R \sim -0.05 \text{ dex kpc}^{-1}$ ) for the gaseous component in the sense that the inner part is more metal-rich. The outer part of the remnant ( $R > 3$  kpc), which is composed mostly of gas ( $f_g > 0.6$ ), shows  $[\text{Fe}/\text{H}] < -0.95$  owing to severe suppression of star formation and the resultant much less efficient chemical enrichment. These results imply that if the

outer gas disk of the remnant is tidally stripped by other giant galaxies, the gaseous stream can be very metal-poor. The new stars also show a negative yet weak metallicity gradient ( $\Delta[\text{Fe}/\text{H}]/\Delta R \sim -0.03 \text{ dex kpc}^{-1}$ ) as a result of inward transfer of gas chemically polluted by supernova. Thus the present chemodynamical simulations demonstrate that dissipative dwarf-dwarf merging can transform two dIs into one dwarf that has both a stellar spheroid with younger, more metal-rich stellar population in its inner part and an extended, more metal-poor outer gas disk.

#### 4. Discussion and conclusions

Although previous numerical simulations of galaxy merging with large gas mass fractions and unique orbital configurations have already reproduced dynamically hot stellar spheroids with extended gas disks or polar-rings (Bekki 1998), the present study has first shown the formation of stellar spheroids with extended gas disks with rotation from gas-rich *dwarf-dwarf merging*. We confirm that the formation processes of dwarf spheroidal with extended gas disks do not depend so strongly on model parameters as long as the merger precursor dI has an extended gas disk: the size ratios of stellar disks to gaseous ones in dIs can be a key parameter that controls physical properties of the remnants of dwarf-dwarf merging.

The present study has first suggested a scenario in which both the stellar spheroid and the extended HI gas disk with rotation in the SMC could have been formed in an ancient dissipative dwarf-dwarf merger event. The observed hot kinematics of older stellar populations can be thus due to violent dynamical relaxation associated with the merging. The observed kinematical differences between older stellar and gaseous components in the SMC result from differences in dynamical evolution between the two components during the merging. In this scenario, the SMC with an extended HI disk interacted strongly with the LMC and the Galaxy from 2 – 3 to 0 – 0.2 Gyrs ago (e.g., Bekki & Chiba 2007) so that it could lose the gas disk and then finally can become the present SMC: the merging happened much earlier than the recent LMC-SMC-Galaxy interaction. The stripped HI gas is now observed to be either the Magellanic Stream (MS) or the Magellanic Bridge (MB).

If this scenario is correct, then when did the SMC experience such a dwarf-dwarf merger event? Since stellar populations formed before the merger event should have dynamically hot kinematics in this scenario, the youngest age of stellar populations that show *both* spheroidal distributions and no or little rotation can correspond to the epoch when the merging occurred. Recent observations of AGB stars in the SMC have reported that (i) the average age of the old and intermediate stellar populations is 7 – 9 Gyr and (ii) the stars have a more regular distribution and appear to be a slightly flattened ellipsoid (e.g., Cioni et al. 2000;

2006). However, owing to the lack of observations on dependences of kinematical properties for AGB/RGB stars on their ages, it is currently difficult to derive the youngest age of stars that consist of the possibly dynamically hot spheroid.

Previous models for the formation of the MS and the MB suggested that the distribution of the gaseous component in the SMC is required to be significantly more extended than that of the stellar one (e.g., Yoshizawa & Noguchi 2003; Muller & Bekki 2007). The present scenario naturally explains why the required distribution is possible in the SMC. However, the scenario also predicts that the merger remnant (i.e., the SMC) can have stars with the total mass of about  $10^8 M_\odot$  for  $3 < R < 5$  kpc. This means that the MS and MB can possibly contain stars, if they are formed from tidal stripping, which is more effective in the outer regions of the SMC. The SMC with actively star-forming central regions might well look like a blue compact dwarf (BCD), if it is observed at the epoch when the dwarf-dwarf merging is in the very late stage or just completed (i.e., a high redshift universe). We thus suggest that gas-rich dwarf-dwarf merging can provide a possible evolutionary link between BCDs and dIs with older stellar spheroids (Bekki & Chiba 2008).

Recent observations have reported that some dwarf dIs have old or intermediate-age stellar populations in their halo regions (e.g., Battinelli & Demers 2006; Battinelli et al. 2007; Battinelli et al. 2007; Demers et al. 2006). Some “transition” dwarfs, which are intermediate-class of objects between dIs and dEs/dSphs, are observed to have early-type outer structures and young stellar populations in their centers (e.g., Dellenbusch et al. 2008). Some dwarfs with older stellar spheroids (e.g., NGC 404 and NGC 6822) are observed to have extended HI gas disks (e.g., del Río et al. 2004; Demers et al. 2006). Therefore the SMC is not a rare example of dIs that have older stellar spheroids: understanding the origin of the SMC could help us to better understand the formation and evolution of dwarfs listed above.

Irregular optical appearances of dIs are simply due to inhomogeneous distributions of star-forming regions in *gas disks* and therefore do not provide information on spatial distributions of underlying older stellar populations. The present study suggests that some fraction of dIs with outer spheroids can be merger remnants. Although recent observations have revealed that many dIs have extended low surface brightness structures (e.g., Minniti & Zijlstra 1996; Aparicio & Tikhonov 2000), it is observationally unclear how much fraction of dIs have *spheroids* composed mostly of older stellar populations: the number fraction dIs possibly formed from merging is unclear. It could be possible that *some* of the present dSphs were previously dIs with older spheroids formed by dwarf-dwarf merging and later became dSphs after losing HI gas via tidal and ram pressure stripping. Future numerical simulations of dwarf-dwarf merging with a wide range of model parameters need to discuss this possibility

of dSph formation at very high- $z$ .

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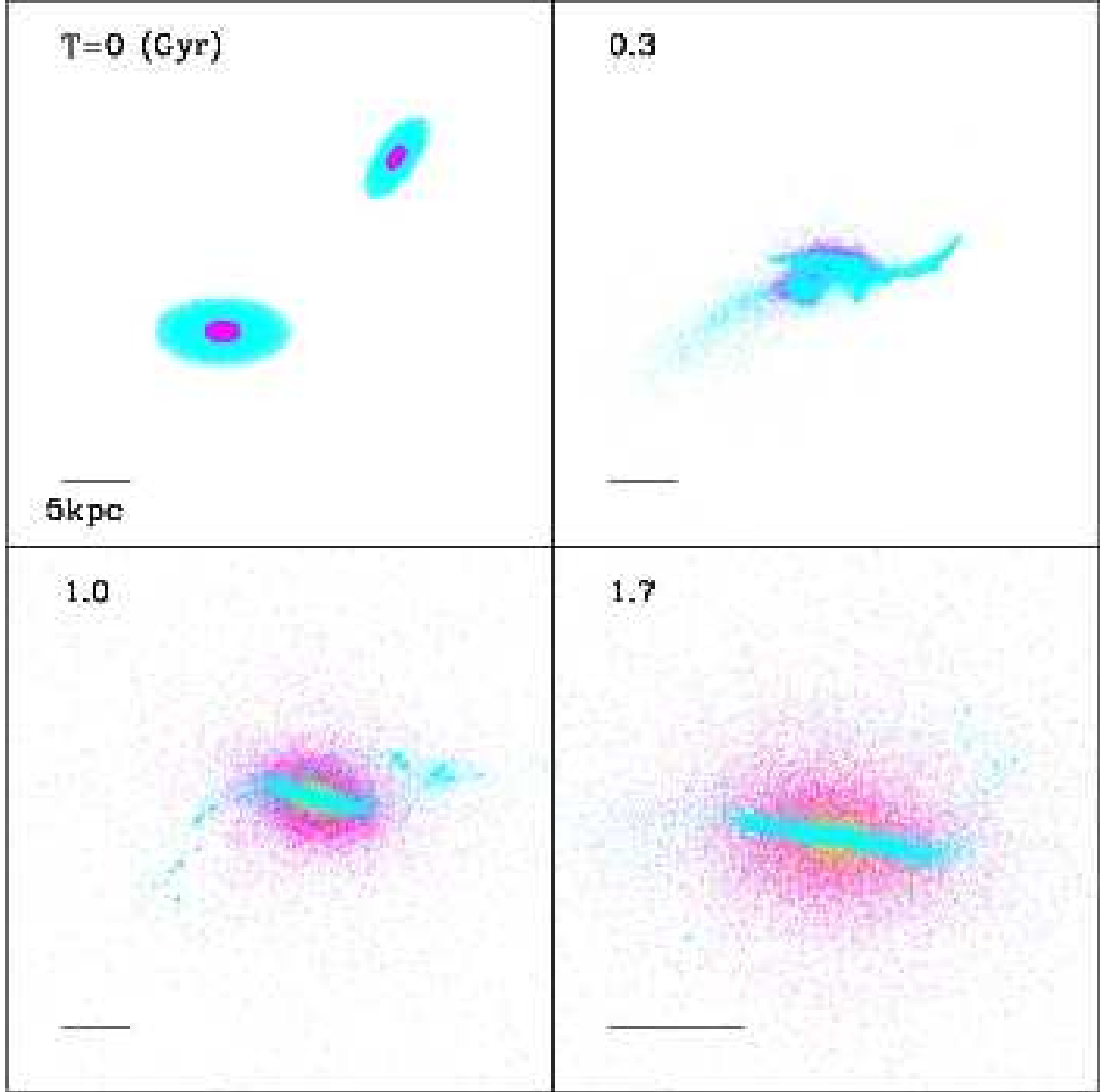


Fig. 1.— Mass distributions of old stars (magenta), gas (cyan), and new stars (yellow) of the unequal-mass dI-dI merger with  $m_2 = 0.5$  projected onto the  $x$ - $z$  plane at four different time steps. The time  $T$  in units of Gyr is shown in the upper left corner of each panel. Frames measure 40 kpc in the first three and 20 kpc in the last so that the extended disk can be more clearly seen at  $T = 1.7$  Gyr. Only old stars can be seen for the central 1.25 kpc of two dIs in the first frame, because the stellar particles are overlaid on gaseous ones: gas particles exist in the central 1.25 kpc.

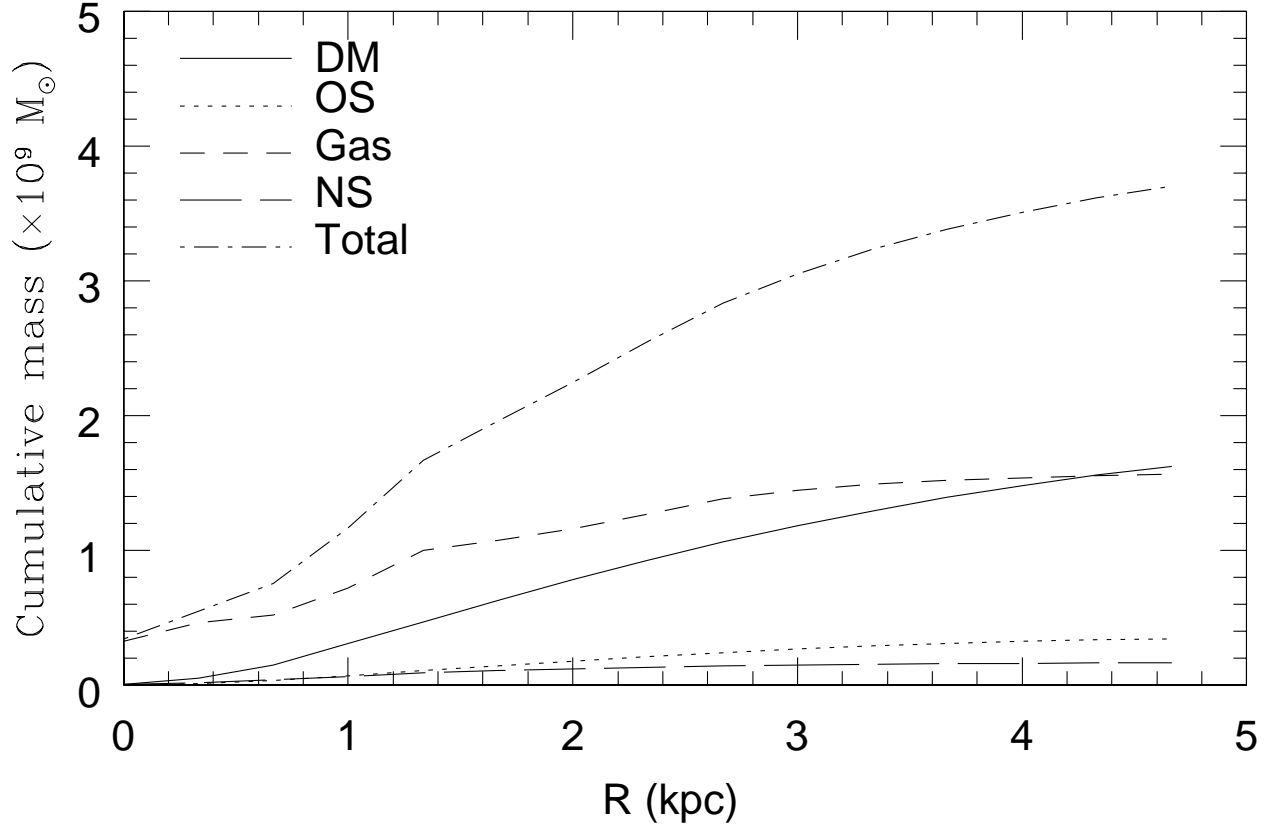


Fig. 2.— The total mass within  $R$  for dark matter halo (solid, referred to as DM), old stars (dotted, OS), gas (short-dashed), new stars (long-dashed), and total (dash-dotted) in the merger remnant.

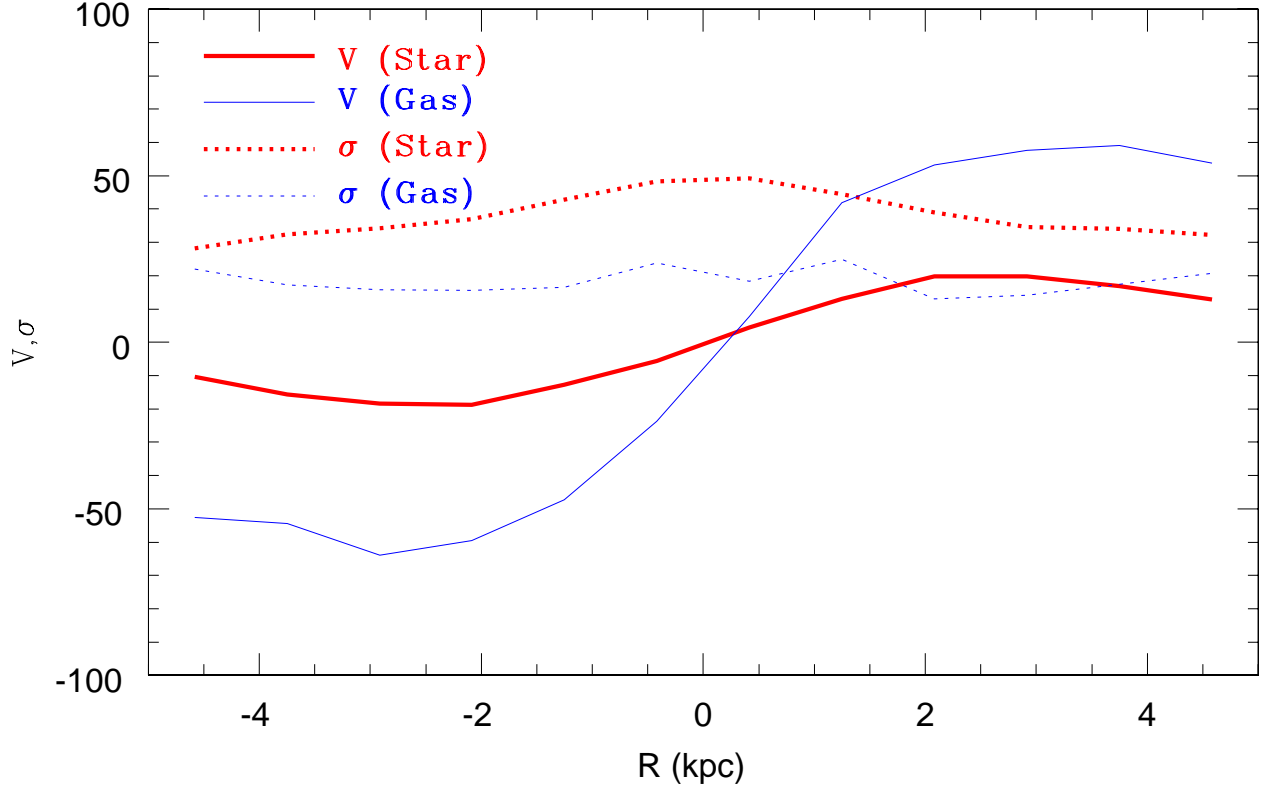


Fig. 3.— The radial dependences of line-of-sight velocities ( $V$ ) for stars (red, thick solid) and gas (blue, thin solid) and dispersions ( $\sigma$ ) for stars (red, thick dotted) and gas (blue, thin dotted) in the merger remnant. Here the remnant is seen from the  $x$ -axis so that the  $y$ -components of velocities of particles are used for the radial  $V$  and  $\sigma$  profiles.

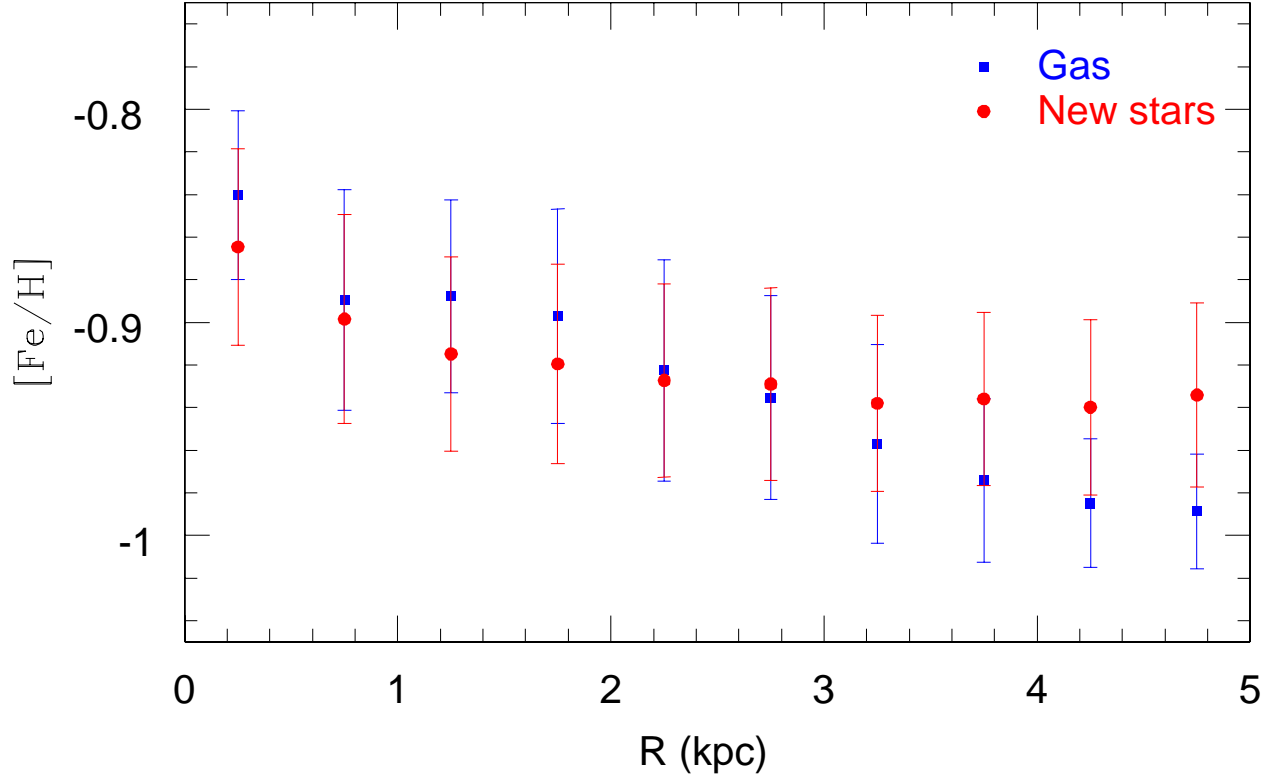


Fig. 4.— Metallicity gradients of gas (squares, blue) and new stars (circles, red) in the merger remnant for the model with the initial gaseous metallicity of  $[\text{Fe}/\text{H}] = -1$ . Note that the outer regions ( $R > 3$  kpc) of the gas disk show metallicities similar to the original ones (i.e.,  $[\text{Fe}/\text{H}] = -1$ ).

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